Optimization of WAAM process to produce AUSC components with increased service life

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Goals and Importance of the Study

- Develop WAAM capability to produce functionally graded AUSC components with local morphology and composition to increase structural life in severe service conditions
- Integrate physics-based material and damage modeling into WAAM to produce and test materials engineered for aggressive environment, extreme high temperature and very long operation time regimes

Key Technologies nuggets

1. WAAM Microstructure Control Strategy
2. Physics-based modeling and prediction of the manufacturing process and resulted materials response
3. Data-driven AM Design & Component Risk Assessment
4. Technoeconomic assessment of WAAM process
5. Machine Learning for Control and Materials design
6. Materials testing and environmental impacts

Business Value/Impact

ICME based microstructural design and machine learning driven optimization tools correlated to test for the enhancement of service life of turbine parts fabricated through WAAM

Prediction of lifing based on composition variation across the part thickness and environmental degradation
Wire-Feed Additive Manufacturing – Tailored Local Composition

Haynes 282 deposits & chromium content variation

- 0.045 wire per AWS A5.14:2018 ERNiCrCoMo-2
  - Base material used for deposition parameter development
- Second wire feeder with a high chromium content feedstock
- Blending of the two wire feeds to locally tailor the chromium concentration, for oxidation performance

<table>
<thead>
<tr>
<th>Preliminary deposition parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Gas Flow</td>
</tr>
<tr>
<td>Shield Gas Flow</td>
</tr>
<tr>
<td>Torch Standoff</td>
</tr>
<tr>
<td>Travel speed</td>
</tr>
<tr>
<td>Main Arc Current</td>
</tr>
<tr>
<td>Wire Feed Rate</td>
</tr>
<tr>
<td>1.2 L/min</td>
</tr>
<tr>
<td>12 L/min</td>
</tr>
<tr>
<td>14 mm</td>
</tr>
<tr>
<td>3.5 to 7.5 mm/s</td>
</tr>
<tr>
<td>150 to 280 A</td>
</tr>
<tr>
<td>1.5 to 4 m/min</td>
</tr>
</tbody>
</table>

- 0.045 wire per AWS A5.14:2018 ERNiCrCoMo-2
  - Base material used for deposition parameter development
- Second wire feeder with a high chromium content feedstock
- Blending of the two wire feeds to locally tailor the chromium concentration, for oxidation performance

Samples with gradients in chromium content, and elevated chromium. The surface layers can be optimized for enhanced oxidation performance.
Wire-Feed Additive Manufacturing – Heat Source Calibration

Instrumented substrate for heat source calibration

- Substrates include thermocouples, embedded in approx 0.050” deep holes
- Four thermocouples, two top surface, two bottom
- LabVIEW system can capture thermal history during multiple layer buildup
- Voltage-current data during build is monitored/recorded
- Robot toolpath/travel speed recorded by robot controller
- Data utilized to calibrate heat source model

Single width bead (no raster pattern), 8 layers height

Heat accumulation during a 10 layer tall deposit
Characterization of samples fabricated using *lower cooling rate* and continuous scans through optical microscopy, pole figures and EBSD.

Fabrication, heat treatment and characterization steps.

<table>
<thead>
<tr>
<th>Fabrication</th>
<th>WAAM with optimized parameter sets for location specific microstructure and twin wire for graded composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-relief</td>
<td>1900°F for duration of 2 hours followed by air cooling</td>
</tr>
<tr>
<td>Solutionizing</td>
<td>2075°F for duration of 1 hour followed by air cooling</td>
</tr>
<tr>
<td>Aging</td>
<td>1850°F for duration of 2 hours followed by air cooling</td>
</tr>
<tr>
<td>Manufacturing inspection test</td>
<td>NDE technologies (Eddy current, Flexible Eddy Current, Phase Array UT, TFM/FMC)</td>
</tr>
<tr>
<td>Microstructure characterization</td>
<td>Optical microscopy (OM), Scanning electron microscopy (SEM), Energy dispersive spectroscopy (EDS), Electron backscatter diffraction (EBSD), Computed Tomography (CT)</td>
</tr>
<tr>
<td>Mechanical Characterization</td>
<td>ASTM Tensile test, creep test, fatigue test, oxidation test</td>
</tr>
</tbody>
</table>

Characterization of samples fabricated using *higher cooling rate* through optical microscopy, pole figures and EBSD.

Particulate found inside grain boundary region.
Optimization of WAAM to Improve Lifing of AUSC Components

Enables:
1. Tailored material property placement for novel part design using functionally graded microstructure and composition,
2. Techno-economic assessment with increased service life,
3. Objective Physics Based criteria for Rules Based Design of WAAM hardware,
4. Features and physical properties not possible through conventional means

WAAM impact on AUSC component design and development.

Product Life Cycle
1. AUSC component development
2. Power or efficiency upgrade evaluations
3. Repair and refurbishment
End-to-End Toolchain Development

Design to manufacturing path

Simulated deposition process

Development of open architecture process chain utilizing Siemens NX digital platform for high deposition rates for high temperature capable materials utilizing WAAM for AUSC components.
Techno-economic Assessment

Process to Component costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Stop Valve</th>
<th>Control Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP (High Pressure)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP (Intermediate Pressure)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cellular Automata (CA) model of crystal growth

**Computationally Efficient Method to Predict Process Effect on Crystallographic Structure and Composition**

Transition conditions for the CA model.

<table>
<thead>
<tr>
<th>State of the cell before transition</th>
<th>Transition condition</th>
<th>State of the cell after transition</th>
<th>Transition condition for</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_i &gt; 0$</td>
<td>$T_i = T_c$</td>
<td>$S_i = 0$</td>
<td>Melting</td>
</tr>
<tr>
<td>$S_i = 0$</td>
<td>A grain is nucleated in the $i$th cell</td>
<td>$S_i = 1$</td>
<td>Nucleation</td>
</tr>
<tr>
<td>$S_i = 0$</td>
<td>The $i$th cell is captured by a neighboring cell</td>
<td>$S_i = 1$</td>
<td>Capture</td>
</tr>
<tr>
<td>$S_i = 1$</td>
<td>The envelope centered at the $i$th cell has encompassed all the neighboring cells</td>
<td>$S_i = 2$</td>
<td>Envelope growth</td>
</tr>
</tbody>
</table>

$v(\Delta T) \sim (\Delta T)^{2.5}$

Temperature on Centerline

CL/GD Distribution

Temperature 2D Distribution

Elapsed Time: $2.4096 \times 10^{-3}$
Effect of Crystal Nucleation on Microstructure

1) 2D model 400X400 cells
2) Initial temperature distribution analytical or from CFX
3) 3 domains with properties: argon, liquidus and substrate
4) Thermal solver with cooling at the bottom and adiabatic on the sides and top
5) Random initial nucleation (bulk, substrate, gas/liquidus boundary)
6) Explicit time marching

- Coarser grains start forming after few fine surface grains.
- Bulk nucleation/3D influence is present.
- Coarser grains at top.
Machine Learning

Objective

- Develop a data-driven framework to establish the processing-structure relationship
- Synthesize a deep learning based approach that models the processing-structure relationship as a conditional image synthesis problem

Quantitative Analytics

Task: Develop a neural network architecture to generate microstructures, or to directly predict microstructure characteristics, from the process parameters and/or time series of sensor measurements of the process
Materials Testing and Environmental Impacts

Correlation of microstructure to properties

Comparison to conventional H282 properties

Mechanical and environmental testing of H282 to be compared to baseline
Materials Testing and Environmental Impacts

- Evaluate materials performance at different intervals to track materials microstructure/property changes with time/temperature through miniature thermal/mechanical testing.
- Analyze the multi-axial structural life and environmental effect assisted-damage progression of Haynes 282 specimens.

Oxidation characteristics for A-USC conditions

Deodeshmukh and Pint, 2019

Mechanical and environmental testing of H282 to be compared to baseline
**Reaction-Diffusion Oxidation Model**

*Chromia scale grows to the left, alumina grows to the right along grain boundaries - simultaneously*

**Reaction–Diffusion Model with variable coefficients**

- Assume metal can leave the surface according to
  
  \[ D_{Cr} \frac{\partial [Cr]}{\partial x} = k_{abs} ([Cr] - [Cr]_a) \text{ at } z = 0 \]

- The metal “vapor” is consumed according to
  
  \[ \frac{\partial [Cr]_a}{\partial t} = -r_0 [Cr]_a [O]_a \text{ at } z = 0 \]
  
  \[ [Cr]_a = p_a(T)/(R_a T) \text{ at } t = 0 \]

- The increase in metal oxide is
  
  \[ x_{sc} \frac{\partial (Cr_2O_3)}{\partial t} = k_{abs} ([Cr] - [Cr]_a) \text{ at } z = 0 \]
  
  \[ [Cr]_a = [Cr]_{vapor} \]

- Integrating over \( \Delta t \):
  
  \[ [Cr]_a = [Cr]_{x=0} + ([Cr]_{a=0} - [Cr]_{x=0}) e^{-\frac{k_{abs}x_{sc\Delta t}}{x_{sc}}} \]

- The increase in scale thickness is
  
  \[ (1 - v_f) \rho_{Cr_2O_3} \frac{\partial x_{sc}}{\partial t} = \frac{v_f}{n_{cr}} Mcr_2O_3 r_0 [Cr]_a [O]_a x_{sc} \]

  where \( x_{sc} \) is the scale thickness

  \[ v_f = v_f^0 \left( 1 - \frac{x_{sc}}{x_{sc, max}} \right)^n \text{ if } v_f^0 < 1, 1 - v_f \approx 1 \]

- Additional parameters:
  
  \[ k_{abs}, x_{sc, max}, n, v_f^0, \rho_{Cr_2O_3} \]
Degradation – Physics Based Oxidation prediction

Weight gain used for model parameters verification

Voids evolution stabilizes the scale growth

Chromia scale thickness is used for model parameters calibration
Summary

- Fully dense Haynes 282 coupon fabrication using WAAM and heat treatment of deposited coupons
- Experimental demonstration of microstructure control in Haynes 282 alloy through WAAM (as-deposit and full heat treated) as well as Haynes 282 composition control
  - The optimized parameter sets created near defect/porosity free structure with >99.6% density, thus eliminating need of hot-isostatic pressing (HIP). The scan strategy used in this particular sample involved a zig-zag scan strategy with a forward speed of 3.5 mm/s.
- Model of the weight gain during chromium and aluminum oxidation; development of the model framework for the simultaneous oxidation of Cr and Al in Haynes 282 and the swallow of the oxide layers
- New oxidation mechanism describing simultaneous oxidation of Cr and Al in Haynes 282
- Development of an image-processing pipeline for identifying grains in microstructure images and computing their characteristics such as area, aspect ratio and orientation angles using machine learning (ML)
- A coupled finite difference Cellular automata model (CA) is formulated and implemented to perform stochastic prediction of as-deposit microstructure in Wire Arc Additive manufacturing.
- A “digital twin” of the physical robotic set up has been created
- Development of NX open code has been completed
- Techno-economic Assessment of the WAAM controlled strategy application to valves has been performed
ACKNOWLEDGEMENT

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